

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

**In re application of:** Paul et al.

**Application No.** 10/803,502

**Filed:** March 17, 2004

**Confirmation No.** 5691

**For:** METHOD FOR MAKING DEVICES  
HAVING INTERMETALLIC  
STRUCTURES AND INTERMETALLIC  
DEVICES MADE THEREBY

**Examiner:** Paul A. Wartalowicz

**Art Unit:** 1754

**Attorney Reference No.** 245-68071-01

COMMISSIONER FOR PATENTS  
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CERTIFICATE OF MAILING

I hereby certify that this paper and the documents referred to as being attached or enclosed herewith are being filed by EFS on the date shown below.

Attorney or Agent  
for Applicant(s)

Date Filed

*Shay C. Slater*  
*February 9, 2009*

**DECLARATION BY PROFESSOR BRIAN KEVIN PAUL**

I, Brian Kevin Paul, hereby declare as follows:

1. I am a co-inventor of the subject matter disclosed and claimed in the application referenced above.
2. I have been employed by Oregon State University for the last 14 years. I currently am a full professor in the School of Mechanical, Industrial and Manufacturing Engineering. A copy of my current curriculum vitae is attached hereto as Appendix A.
3. I have read the Office Communication from the United States Patent Office (PTO) dated November 7, 2008. I understand that the Patent Office is seeking additional information to determine if Paul *et al.* "Intermetallic Microlaminations for High-Temperature Microreactors," referred to during prosecution and hereinafter as Paul I, was a "printed publication."

4. In summary, Paul I was not made available to the public in a manner that would constitute "publication" as outlined in the Office Communication. The subject matter of Paul I eventually was published in November of 2002 for the International Mechanical Engineering Congress and Exposition (referred to as the IMECE publication). I understand that the IMECE publication was cited in an Information Disclosure Statement that was submitted to the PTO on October 5, 2005.

Each of the particular questions raised by the Office Communication is addressed below in further detail.

5. The first question asked by the Office Communication is whether Paul I was made available to the public in any form, such as by a file transfer protocol (FTP) within the University, via an online database or made available on the World Wide Web. I have reviewed my records, and confirm that Paul I was not made publicly available by any of these methods until the IMECE publication in November of 2002.

6. The second question asked by the Office Communication is whether Paul I was presented as a poster presentation, as a handout, or as a PowerPoint slide presentation, at any conference or lecture having greater than 50 people present. I have reviewed my records, and confirm that Paul I was not made publicly available by a poster presentation, as a handout, or as a PowerPoint slide presentation, at any conference or lecture having greater than 50 people present, until the IMECE publication in November of 2002.

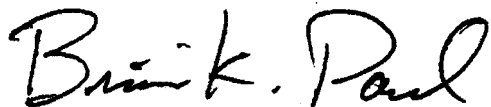
7. The third question asked by the Office Communication is whether Paul I was presented at the 4<sup>th</sup> International Conference of Microreaction Technology in Atlanta, Georgia, from March 5-9, 2000. I have reviewed my records, and confirm that information contained in Paul I was not presented at the 4<sup>th</sup> International Conference of Microreaction Technology in Atlanta, Georgia, from March 5-9, 2000. By reviewing my computer records, I determined that Paul I was initially created on November 28, 2001, more than a year after the 4<sup>th</sup> International Conference of Microreaction Technology in Atlanta, Georgia, on March 5-9, 2000. Microsoft Office PowerPoint slides that were presented at this conference are attached hereto as Appendix B.

8. The fourth question asked by the Office Communication is whether any information of Paul I was "known or used by others," including by other authors named on Paul I. The information stated in Paul I was not known or used by persons other than the co-authors until the IMECE publication. Information concerning the conversion and bonding of nickel and aluminum foils into NiAl microchannel structures without using a bonding assist material was presented at the 4<sup>th</sup> International Conference of Microreaction Technology (ICMT) in Atlanta, Georgia, on March 5-9, 2000. I then prepared Paul I beginning in November of 2001, which contained information concerning new Ni<sub>3</sub>Al sheet materials. The IMECE 2002 publication included the information of Paul I, but also included prior micrographs from the prior ICMT paper mentioned above. The NiAl architecture and a new Ni<sub>3</sub>Al architecture were compared in the IMECE publication. The co-author non-inventors were listed as authors on the IMECE publication because they had originally produced the NiAl SEM micrographs. Kannachai Kanlayasiri and I conceived of the subject matter disclosed and claimed in the present application concerning the use of a bonding material between aluminide laminae completely separate from the co-author non-inventors. As a result, the co-authors are not listed as inventors on the present application.

9. I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Brian Kevin Paul

Date:



February 9, 2009

# INDUSTRIAL AND MANUFACTURING ENGINEERING

## OREGON STATE UNIVERSITY

### College of Engineering

**PAUL, Brian K.**

Professor

**BIRTH DATE**

July 1, 1964

#### DEGREES

Ph.D., Industrial Engineering, The Pennsylvania State University, 1995

M.S., Industrial Engineering, Arizona State University, 1988

B.S., Industrial Engineering, Wichita State University, 1985

#### ACADEMIC POSITIONS

Professor, Oregon State University, 2006-present

Director, Microproducts Breakthrough Institute Nano/Micro Fab, 2005-present

Associate Professor, Oregon State University, 2000-2006

Assistant Professor, Oregon State University, 1995-2000

Laboratory Instructor, The Pennsylvania State University, 1993-1995

#### NON-ACADEMIC POSITIONS

Senior Research Engineer, Battelle Pacific Northwest Laboratories, 1994

Research Engineer, Battelle Pacific Northwest Laboratories, 1990-1993

Manufacturing Consultant, McDonnell Douglas Helicopter Company, 1989

Manufacturing Systems Engineer, Honeywell Industrial Automation Systems, 1986-1989

Industrial Engineer, Boeing Military Airplane Company, 1986

#### RESEARCH INTERESTS

Arrayed microfluidics for green nanosynthesis (e.g. nanoparticle synthesis; macromolecular synthesis; etc.) and microreactor-assisted materials processing (e.g. nanomaterial deposition)

Precision bonding for microsystem packaging (e.g. nanoparticle-assisted bonding; precision adhesive bonding; differential thermal expansion bonding; etc.); and

Packaging of arrayed microfluidic systems for distributed and portable energy, chemical and biomedical applications; especially microlamination (i.e. the patterning and bonding of thin layers of material)

#### PROFESSIONAL SOCIETIES

- American Society of Mechanical Engineers
- American Society for Precision Engineering
- Institute of Industrial Engineers
- Society of Manufacturing Engineers

#### PROFESSIONAL ACTIVITIES

- Scientific Committee, North American Manufacturing Research Conference, 2008-11
- Associate Editor, *ASME J Mfg Sci and Engr*, One of 12 Assoc. Ed., nano/micro fab, 2004-2007.
- Associate Editor, *SME J Mfg Processes*, referee two to four papers per year, 2000-present.
- Invited session chairman for Nano/Micro Manufacturing Systems at the 2006 IERC
- Co-editor for special issue on Multi-Scale Fabrication in the *J Mfg Processes*, Spring 2004.
- Invited session chairman for Multi-Scale Manufacturing at the 2002 ASME IMECE Congress, Manufacturing Engineering Division
- Scientific Committee, North American Manufacturing Research Conference, 2001-03

- Society of Manufacturing Engineers, Student Chapter Advisor, 1996-2002, 2005

## PROFESSIONAL RECOGNITION

- 2007 Runner-up, Best Student Paper, North American Manufacturing Research Conference.
- Invited Chair, Nano/Meso/Micro Manufacturing Tech. Comm., ASME MSEC, 2007-08.
- Invited Session Chair, Nano/Micro Manufacturing Systems at IERC, 2006.
- 2004 Indo-US Forum on Advanced Manufacturing, Kanpur, India
- One of 12 Invited Speakers at the 2003 ASPE National Conference
- 2003 OSU College of Engineering Research Collaboration Award
- Invited Guest Editor, *SME J Mfg Processes*, organized special issue for J Mfg Processes on Multi-scale Fabrication, 2002-2003.
- Invited Session Coordinator, Multi-scale Fabrication at ASME IMECE, 2002.
- 2000 Hamed K. Eldin National Engineering Design and Automation Young Faculty Award, presented at the 5th Int'l Conf. on Engineering Design and Automation.
- 2000 Engelbrecht Young Engineering Faculty Award, OSU College of Engineering
- 1999 National Academy of Engineering Frontiers of Engineering Workshop, one of 35 invited academicians
- Office of Naval Research Young Investigator, 1998-2001
- Pacific Northwest National Laboratory Affiliate Staff Scientist, 1997-2001
- Society of Automotive Engineers Doctoral Fellowship, 1992-1995
- Benjamin Niebel Manufacturing Fellowship, 1992-1993
- Honeywell Industrial Fellow in Computer-Integrated Manufacturing, 1986-1988

## PUBLICATIONS

### Book Chapters

- Paul, B.K., "Micro Energy and Chemical Systems and Multi-scale Fabrication," Chapter 14 in *Micromanufacturing and Nanotechnology*, Springer-Verlag, Germany, 2005.
- Paul, B.K., Chapter 28 "Non-Traditional Machining"; Chapter 33 "Rapid Prototyping and Freeform Manufacturing"; and Chapter 34 "Microelectronic Manufacturing and Electronic Assembly" in *Materials and Processes in Manufacturing*, 9<sup>th</sup> Ed., DeGarmo, Black and Kohser (Eds.), Wiley, 2003.
- Paul, B.K. and C.O. Ruud, "Rapid Prototyping and Freeform Manufacturing," in *Integrated Product, Process and Enterprise Design*, B. Wang (Ed.), Chapman & Hall, London, England, 1997.
- Levine, L.O. and B.K. Paul, "Implementing Technology to Enhance Agility," in *The Transition to Agile Manufacturing: Staying Flexible for Competitive Advantage*, J.C. Montgomery and L.O. Levine (Eds.), American Society for Quality Control, Milwaukee, WI, 1995.
- Spiker, B.K. and B.K. Paul, "Change and Manufacturing People," in *Success Factors for Implementing Change: A Manufacturing Viewpoint*, K. Blache (Ed.), Society of Manufacturing Engineers, Dearborn, MI, 1988.

### Archival Journal Publications

- Paul, B.K., S. Bose, and D. Palo, "An internal convective heating technique for diffusion bonding arrayed microchannel architectures," *J Mfg Proc.*, in first review.
- Paul, B.K., B.S. Abhinkar and S. Lee, "Compression seals for embedding membrane microvalves in arrayed microfluidic devices," *J. Micromech. Microeng.*, in first review.
- Doneanu, A., Rundel, J.T., Tseng, T., Paul, B.K. and Remcho, V.T., "Development of a chip-based high-throughput nanoextractor," *J. Electrophoresis*, in first review.

- C. Chang, B.K. Paul, V.T. Remcho, S. Atre, J.E. Hutchison, "Synthesis and post-processing of nanomaterials using microreaction technology," *J Nanoparticle Res.*, 10(6): 2008.
- Liu, S., C. Chang, B.K. Paul, and V.T. Remcho, "Convergent synthesis of polyamide dendrimer using a continuous flow microreactor," *Chem. Engr. Journal*, 135(1), 2008, S333-S337.
- RB Peterson, BK Paul, T Palmer, Q Wu, W Jost, C Tseng, S Tiwari, G Patello, EC Buck, JD Holladay, R Shimskey, P Humble, P MacFarlan and J Wainright, Radiolytic microscale power generation based on single chamber fuel cell operation, *J. Micromech. Microeng.* 17 (2007) S250-S256.
- C. Pluess and B. Paul, "Application of Controlled Thermal Expansion in Microlamination for the Economical Production of Bulk Microchannel Systems," *Chem Engr Comm*, 194(9): 2007, 1259 - 1270.
- Rundel, J.T., B.K. Paul, V.T. Remcho, "Organic Solvent Nanofiltration for Microfluidic Purification of PAMAM Dendrimers," *J Chrom A*, 1162(2), 2007, 167-174.
- Paul, B.K., P. Kwon and R. Subramanian, "Understanding Limits on Fin Aspect Ratios in Counterflow Microchannel Arrays Produced by Diffusion Bonding," *J. Mfg Sci. Engr*, 128(4): 977-983, 2006.
- Amer, N., W.C. Hurlbut, B.J. Norton, Y-S Lee, S. L. Etringer and B. K. Paul, "Terahertz wave propagation in one-dimensional periodic dielectrics," *Applied Optics*, 45(8): 1857-1860, 2006.
- Paul, B.K., N. Sharma and T. Doolen, "Microlamination Based on Surface Mount Technology for the Economical Production of High-Aspect-Ratio Microchannel Arrays," *J Mfg Processes*, 7(2): 174, 2005.
- Wattanuchariya, W. and B.K. Paul, "The Effect of Fixture Compliance on Thermally-Enhanced Edge Registration in Microlamination," *J. Mfg Sci. Engr*, 126(4): 845, 2004.
- Kanlayasiri, K., and B.K. Paul, "A Nickel Aluminide Microchannel Array Heat Exchanger for High-Temperature Applications," *J. Mfg Processes*, 6(1): 17-25, 2004.
- Wattanuchariya, W. and B.K. Paul, "Bonding Fixture Tolerances for High-Volume Metal Microlamination Based on Fin Buckling and Laminae Misalignment Behavior," *J Intl Soc Prec Engr Nanotechnology*, 28(2): 117-128, 2004.
- Paul, B.K. and J. Thomas, "Thermally-Enhanced Edge Registration (TEER) for Aligning Metallic Microlaminated Devices," *J. Mfg Processes*, 5(2): 185-193, 2003.
- Paul, B.K. and V. Voorakarnam, "Effect of Layer Thickness and Orientation Angle on Surface Roughness in Laminated Object Manufacturing," *J. Mfg Processes*, 3(2): 94-101, 2001.
- Paul, B.K., R.D. Wilson, E. McDowell, and J. Benjarattananon, "A study of weld strength variability for automating the capacitor discharge welding process," *Sci Tech. Weld. Joining*, 6(2): 109-115, 2001.
- Paul, B.K., W. Thaneepakorn, and R. Wilson, "The effect of capacitor discharge welding on single crystal metals," *J Mfg. Processes*, 2(3): 143, 2000.
- Paul, B.K. and T. Terhaar, "Comparison of two passive microvalve designs for microlamination architectures," *J Micromech Microengr*, 10: 15-20, 2000.
- Paul, B.K., "An analytical model of the diffusive scattering of low-energy electrons in electron beam resists," *Microelectronic Engr*, 49: 233-244, 1999.
- Paul, B.K., R.D. Wilson, and W. Wattanuchariya, "Application of vacuum chucks to capacitor-discharge welding," *Intl J Flex Automation Integr Mfg*, 5(3&4): 203-215, 1997.
- Paul, B.K., "Effects of Gas Pressure on Low-Pressure Electron-Beam Lithography," *Scanning*, 19: 466-8, 1997.
- Paul, B.K. and M. Klimkiwicz, "Application of an Environmental Scanning Electron Microscope to Micro-Mechanical Fabrication," *Scanning*, 18: 490, 1996.
- Paul, B.K. and S. Baskaran, "A Review of Particulate Materials Processing in Additive Freeform Fabrication," *Reviews in Particulate Materials*, 4: 105, 1996.

- Paul, B.K. and Cochran, J.K., "Qualitative Modeling of the Organizational Acceptance of Advanced Manufacturing Technologies," *Intl J Human Factors Mfg*, 5(2): 177-209, 1995.
- Billo, R.E., R. Rucker, and B.K. Paul, "Three Rapid and Effective Requirements Definition Modeling Tools: Evolving Technology for Manufacturing Systems Investigations," *Intl J Computer Integr Mfg*, 7, 3, 186-, 1993.
- Cochran, J.K. and B.K. Paul, "QUAL: A Microcomputer System for Qualitative Simulation," *Simulation*, 55, 5, 300-308, 1990.

#### **Patents**

- Chaplen, F., P. McFadden, T. Plant, B.K. Paul, G. Jovanovic, J. Trempey, W. Kolodziej, B. Gerwick, C. Willard and J. Liburdy. "Methods for Detecting Bioactive Compounds," US patent number 6,913,877, July 5, 2005.
- Paul, B.K., R. Peterson and T.J. Terhaar. "Microlamination Method for Making Devices," US patent number 6,793,831, September 21, 2004.
- Paul, B.K., R.D. Wilson and D.E. Alman. "Method for Making Devices Having Intermetallic Structures and Intermetallic Devices Made Thereby," US patent number 6,672,502, January 6, 2004.

#### **Patent Applications**

- Paul, B.K., Chang, C. and S. Tiwari, "Microreactor-Assisted Nanoparticle Deposition of Ni for Assisting the Diffusion Bonding/Brazing of MECS Devices," OSU Patent Application, May 2008.
- Paul, B.K. and R. Peterson, "Radial Diffusion Bonding of MECS Devices," OSU Patent Application, April 2008.
- Paul, B.K. and A. Garrison, "Interdigital micromixer for scaled-up, nanomaterial production," OSU Patent Application, March 2008.
- Paul, B.K. and P. Paulraj, "Method to produce microchannel arrays using electronic assembly processes," OSU Patent Application, December 2007.
- Chang, C-H., B.K. Paul and V.T. Remcho, "Microchemical Microfactories," OSU patent application, 2004.
- Paul, B. and G.N. Jovanovic, "Microwave Welding for Polymer and Ceramic Microlamination," OSU Provisional Patent Application, September 2005.
- Jovanovic, G., Paul, B., Atre, S., Simonson, J., Remcho, V., Chang, C. "MICROFLUIDIC DEVICES, PARTICULARLY FILTRATION DEVICES COMPRISING POLYMERIC MEMBRANES, AND METHOD FOR THEIR MANUFACTURE AND USE," OSU patent application, October 2005.
- Chang, C.-H., B.K. Paul and V.T. Remcho, "MICROCHEMICAL NANOFACTORIES," OSU patent application, March 18, 2005.
- Paul, B.K., C. Pluess, T. Doolen and N. Sharma, "HIGH VOLUME MICROLAMINATION PRODUCTION OF DEVICES," OSU Patent Application, October 2004.

#### **Invention Disclosures**

- Paul, B.K. and G.N. Jovanovic, "Floating Particle Microreactors," OSU Invention Disclosure, January 2005.
- Jovanovic, G., M.K. Drost and B.K. Paul, "Production of Hydrogen via Steam Reforming of Biodiesel in Microchannel Reactors," OSU Invention Disclosure, March 2004.
- Paul, B.K. "Development of Pre-Bonding and Convective Heat Transfer Methods for Microlamination of Large Microfluidic Devices," OSU Invention Disclosure, October 2002.

Wattanutchariya, W. and B.K. Paul, "High Volume Fixturing for Microlamination," OSU Invention Disclosure, July 2002.

#### **Refereed Conferences**

- Tiwari, S.K. and B.K. Paul, "Application of nickel nanoparticles in joining stainless steel surfaces," *ASME International Conference on Manufacturing Science and Engineering*, October 7-10, 2008, Evanston, IL.
- Tseng, C.T. and B.K. Paul, "Comparison of Mixing Approaches in the Synthesis and Deposition of Ceria Nanoparticles," *ASME International Conference on Manufacturing Science and Engineering*, October 15-17, 2007, Atlanta, GA.
- Tiwari, S.K. and B.K. Paul, "Fabrication of TiO<sub>2</sub> and SiO<sub>2</sub> Thin Films by Room Temperature Liquid Phase Deposition," *ASME International Conference on Manufacturing Science and Engineering*, October 15-17, 2007, Atlanta, GA.
- Tseng, C.T. and B.K. Paul, "Comparison of Batch Mixing and Micromixing Approaches in the Synthesis and Deposition of Ceria Nanoparticles," *Transactions of NAMRI*, 35, Ann Arbor, MI, May 23-25, 2007.
- Tiwari, S. and B.K. Paul, "Fabrication of Transparent Silica Thin Film by Room Temperature Deposition from a Sol," *Transactions of NAMRI*, 35, Ann Arbor, MI, May 23-25, 2007.
- Paul, B.K. and C. Pluess. "Controlled Application of Differential Thermal Expansion in the Diffusion Bonding of Bulk Microfluidic Devices," *Transactions of NAMRI*, Vol. 34, Milwaukee, WI, May 23-26, 2006, 571-578.
- Paul, B.K., C. Aramphongphun, F. Chaplen, and R. Upson. "An Evaluation of Packaging Architectures for Tissue-based Microsystems," *Transactions of NAMRI*, Vol. 31, Hamilton, Ontario, Canada, May 20-23, 2003.
- Paul, B.K., H. Hasan, T. Dewey, D. Alman, and R.D. Wilson, "An Evaluation of Two Methods for Producing Intermetallic Microchannels," *ASME IMECE*, New Orleans, LA, MEMS Division, November 2002, pp 261-266.
- Porter, J.D., B.K. Paul and B. Ryuh, "Cost Drivers in Microlamination based on a High-Volume Production System Design," *ASME IMECE*, New Orleans, LA, MEMS Division, November 2002, paper no. IMECE2002-32896.
- Thomas, J. and B.K. Paul, "Thermally-Enhanced Edge Registration (TEER) for Aligning Metallic Microlaminated Devices," *Transactions of NAMRI*, Vol. 30, West Lafayette, IN, May 21-24, 2002.
- Gabriel, M., B.K. Paul, R.D. Wilson, and D.E. Alman, "Characterization of Metallic Foil Joints Using Diffusion Bonding and Diffusion Soldering in Microtechnology-based Energy and Chemical Systems," *Transactions of NAMRI*, Vol. 29, Gainesville, FL, 2001.
- Alman, D.E., R.D. Wilson, and B.K. Paul, "Fabrication of NiAl Intermetallic Reactors for Microtechnology-based Energy and Chemical Systems," *Transactions of NAMRI*, Vol. 29, Gainesville, FL, 2001, pp. 453-460.
- Paul, B.K., H. Hasan, J. Thomas, R. Wilson, and D. Alman, "Limits on Aspect Ratio in Two-fluid Micro-scale Heat Exchangers," *Transactions of NAMRI*, Vol. 29, Gainesville, FL, 2001, pp 461-8.
- Paul, B.K. and R.B. Peterson, "Microlamination for Microtechnology-based Energy, Chemical, and Biological Systems," *ASME IMECE*, Nashville, Tennessee, AES Volume 39, November 15-20, 1999, pp 45-52.
- Wilson, R.D. and B.K. Paul, "Rapid Solidification Joining of Non-Ferrous Materials," *Proceedings of the First Intl. Non-Ferrous Processing and Technology Conference*, St. Louis, MO, March 10-12, 1997, ASM Intl.: Materials Park, OH, pp. 435-443.



### Invited Speaker

- Paulraj, P. and B.K. Paul, "SMT Microlamination for Microchannel HX Applications," Surface Mount Technology Association, Corvallis, OR, October 2005.
- Paul, B.K., S. Atre, C. Chang and V. Remcho, "MBI Nano/Micro Fabrication Facility," 2<sup>nd</sup> Annual Micro/Nano Breakthrough Conference, Portland, OR, July 2005.
- Paul, B.K., "Distributed Energy and Chemical Systems and Multi-Scale Fabrication," First Indo-US Workshop on Advanced Manufacturing, Kanpur, India, March 2004.
- Paul, B.K., "Microtechnology-based Energy and Chemical Systems and Multi-Scale Fabrication," ASPE National Conference, Portland, OR, October 2003.
- Paul, B.K., C. Wu, W. Wangwacharakul, J. Liburdy, T. Plant, and G.N. Jovanovic, "Development of passive micro-ball valves (MBV) for biotechnology applications," ACS National Conference, San Diego, April 2-5, 2001.
- Paul, B.K., "Microlamination for Microtechnology-based Energy, Chemical, and Biological Systems," *Microchemical Systems and Their Applications*, Invitation-only DARPA workshop, 16-18 June, Washington, DC, 1999.
- Paul, B.K., "Additive Freeform Microfabrication," *ASM Materials Solutions '97*, 15-18 September, Indianapolis, IN, 1997.
- Paul, B.K. and R.D. Wilson, "Rapid Solidification Joining of Microwires," *National Academy of Sciences, Advanced Material Processing Symposium*, May 22, 1997.

### Conference Proceedings

- Tagore, R., B.K. Paul, J.T. Rundel, V.T. Remcho, H. Jin, C.-H. Chang, L. McKenzie and J. Hutchison, "Fabrication of Microchemical Nanofactory for Scaling Synthesis of Gold Nanoparticles," Sixth Int'l Workshop on Microfactories, Evanston, IL, Oct 2008: 81-85.
- Hendrix, T., D. Palo, C. Chang and B.K. Paul, "Nanotechnology Enhancements to Microtechnology: Pathways to System Miniaturization in Advanced Energy Conversion Systems," ASME Energy Nanotechnology International Conference, Jacksonville, FL, 2008.
- Garrison, A. and B.K. Paul, "Design of an Interdigital Micromixer for Nanoparticle Manufacturing Using Computational Fluid Dynamics," International Conference on Micromanufacturing, Pittsburgh, PA, 2008.
- Han, S.-Y., S. Liu, J. Y. Jung, C.-H. Tseng, S.-O. Ryu, T.-J. Lee, B.K. Paul and C.-H. Chang, "DEPOSITION OF NANOSTRUCTURED THIN FILMS BY MICROREACTOR-ASSISTED CHEMICAL PROCESSES," Intl. Symp. Chem. React. Engr., Kyoto, Japan, 2008.
- Rundel, J.T., B.K. Paul, and V.T. Remcho, "Fabrication of a Bulk Microfluidic Nanofiltration System for the Processing of Macromolecules," International Conference on Micromanufacturing, Greenville, SC, 2007.
- Paul, B., D. Palo and S. Bose, "Internal Convective Heating for Metal Microchannel Bonding," International Conference on Micromanufacturing, Greenville, SC, 2007.
- Abhinkar, B.S., S. Lee and B.K. Paul, "A Conformal Membrane Microvalve for the Plug-Flow Reaction of Nanomaterials," IERC, 2007.
- Rundel, J.T., B.K. Paul and V.T. Remcho, "Organic Solvent Nanofiltration for On-Chip Extraction of PAMAM Dendrimer," *21st International Symposium on Microscale Bioseparations*, CASSS, Vancouver, Canada, January 14-18, 2007.
- Abhinkar, B., B.K. Paul, H. Jin, C. Chang, C. Koch, V.T. Remcho, L. McKenzie and J. Hutchison, "Progress Towards the Synthesis and Extraction of Monodispersed Au Nanoparticles Using Solution-based Microreactors," ANQUE 6, December 2006.
- Rorrer, G.L., A. Goodwin and B. Paul, "Conversion of Glucose to Hydrogen Gas by Supercritical Water within a Microchannel Reactor," Conference Proceeding of AIChE Annual Meeting, San Francisco, CA, November 16, 2006.

- Paul, B.K., B. Abhinkar, T. Tseng, S.-H. Liu, C.-H. Chang, J.T. Rundel, V. T. Remcho, A. Doneanu and Y. Tennico, "A Microchemical Nanofactory for the Production of Dendritic Polymers," Industrial Engineering Research Conference, Orlando, FL, May 20-24, 2006.
- S.-H. Liu, C.-H. Chang, B.K. Paul, V.T. Remcho and B. Abhinkar, "Convergent Synthesis of Dendrimers using Continuous Flow Microreactors," session 62 Polymerization in Micro-Reactors, Conference Proceeding of AIChE Spring National Meeting, Orlando FL, April 24 2006.
- Pluess C. and B.K. Paul, "Application of Controlled Thermal Expansion in Microlamination for the Economical Production of Bulk Microchannel Systems," IMRET8 – 8<sup>th</sup> International Conference on Microreaction Technology, Atlanta, GA, April 2005.
- Chang, C.-H., S.-H. Liu, Y. Tennico, J.T. Rundel, V. T. Remcho, E. Blackwell, T. Tseng and B.K. Paul, "Progress Towards Chip-Based High-Throughput Dendrimer Synthesis," IMRET8 – 8<sup>th</sup> International Conference on Microreaction Technology, Atlanta, GA, April 2005.
- Plant, T., F. Chaplen, G. Jovanovic, W. Kolodziej, J. Trempy, C. Willard, J. Liburdy, D. Pence, and B.K. Paul, "Sensitive cell-based fish chromatophore biosensor," Proc. of SPIE, Vol. 5321, BIOS 2004/Photonics West, January 25, 2004, San Jose, CA.
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- Sharma, N. and B.K. Paul, "The Application of Surface Mount Technology to Multi-Scale Process Intensification," *ASPE National Conference*, Portland, OR, October 2003.
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- Kroon, J., C.-H. Chang, F. Nwachukwu, B.K. Paul, "Investigation of Microreaction Technology for the Production of Semiconductor Nanocrystals," IMRET7 - 7<sup>th</sup> International Conference on Microreaction Technology, Lausanne, Switzerland, September 7-10, 2003.
- Sharma, N., J.D. Porter and B.K. Paul, "Understanding Cost Drivers in Microlamination Approaches to Microsystem Development," *Ind. Engr. Research Conf.*, Portland, OR, May 18-20, 2003.
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- Wattanuchariya, W. and B.K. Paul, "Bonding Fixture Tolerances for High-Volume Metal Microlamination Based on Fin Buckling and Laminae Misalignment Behavior," *ASPE Annual Meeting*, October 20-25, 2002.
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- Chintapalli, P., C. Pluess and B.K. Paul, "Microlamination Based on Differential Thermal Expansion for Diffusion Bonding Bulk Microsystems," poster at *2<sup>nd</sup> Annual Micro/Nano Breakthrough Conf.*, July 2005, Portland, OR.
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- Paul, B.K., "Development of radial diffusion bonding techniques," \$21K, in R. Peterson et al. "Tactical Energy Systems," Army CERDEC, \$4M, 6/15/08-12/31/08.
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#### EDUCATIONAL AND DEVELOPMENTAL GRANTS

- V.T. Remcho and B.K. Paul, "Zeiss Laser Scanning Microscope," Hewlett Packard (donation), brand new \$970K, 2005.
- B.K. Paul and S.V. Atre, "CM Rapid Temp 1512GSH<sub>2</sub>FL Inert Gas Furnace," CM Furnaces/Oregon State University Research Office, \$69,250, 2004.
- B.K. Paul, F. Chaplen and V. Remcho, "ESI 4420 Laser Micromachining System," Electro Scientific Industries/Oregon State University Research Office, \$364,000, 2002.
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- Paul, B.K. and S. Baker, "Development of a Production Engineering Laboratory Based on Context Learning Principles," SME Education Foundation, \$54,108, 1996-97.
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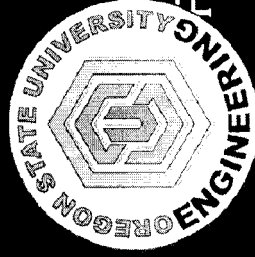
# **INTERMEDIATE MICROLAMINATION FOR HIGH-TEMPERATURE MICROELECTRONICS**

**BRIAN K. PAUL**

**MICROTECHNOLOGY-BASED ENERGY  
AND CHEMICAL SYSTEMS (MECS)  
INITIATIVE**

**DAVID ALMAN AND R. D. WILSON**

**ALBANY RESEARCH CENTER  
COLLEGE OF**



**ENGINEERING  
REGION STATE UNIVERSITY**





# PROBLEM

- Need for materials to support high-temperature microreactors
  - Catalytic combustion
  - Synthesis of HCN
  - Steam superheating for gas turbines
  - Waste heat recovery
- Binder removal in ceramics
  - Warpage
  - Low fractional densities



# INTERMETALLIC

## MICROREACTORS

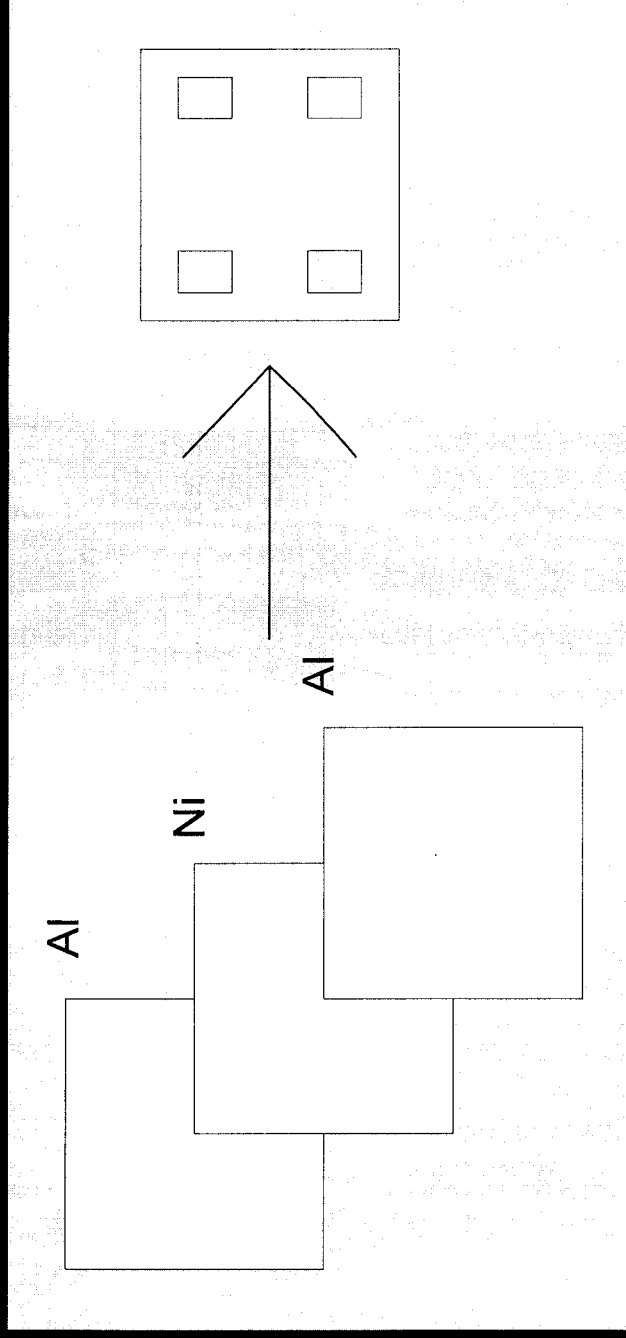
- **Aluminides – NiAl, FeAl,  $\gamma$ -TiAl**
  - Good high-temperature strength/toughness
  - Good corrosion resistance
  - Moderate thermal conductivity
  - Poor formability at room temperature
- **Intermetallics have been synthesized at high temperatures from elemental foils**
- **Microreactors have been laminated from elemental foils**



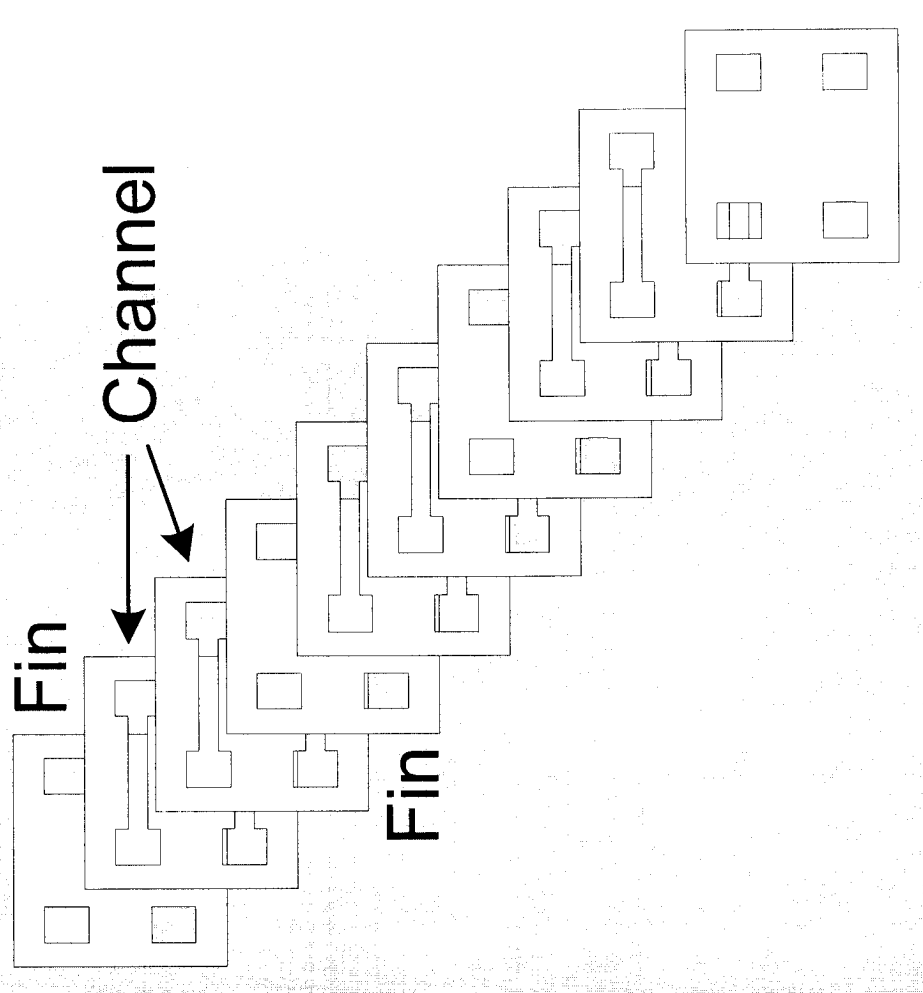
# APPROACH

## A. Lamina formation (100 $\mu\text{m}$ thick)

1. Tack Ni and Al foils
2. Laser micromachine composite



# APPROACH

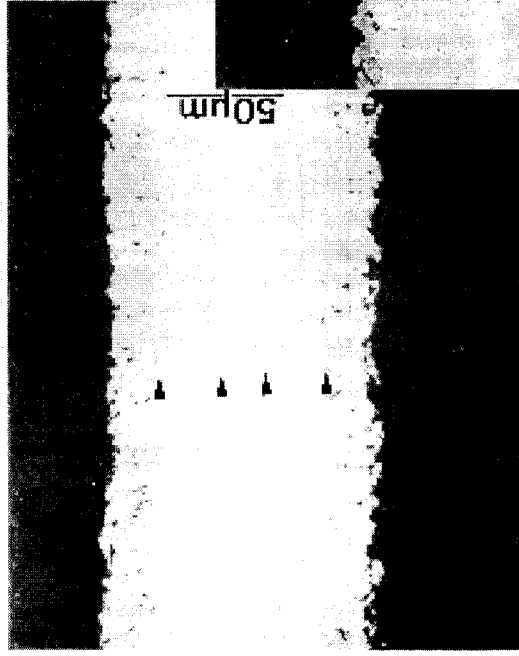


## B. Laminar bonding

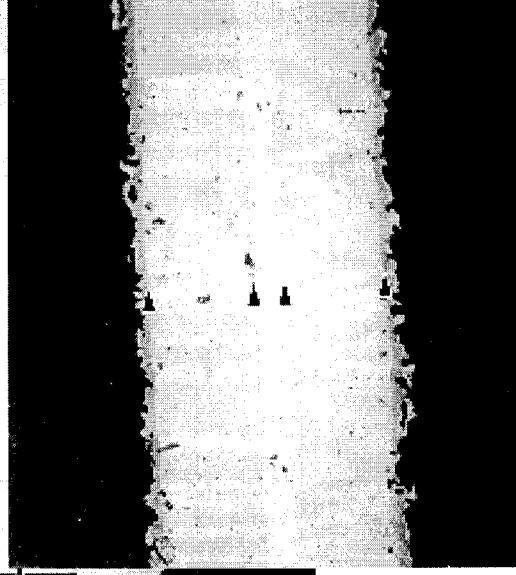
1. Align
2. Liquid-phase bond
  - Bonding
  - Conversion



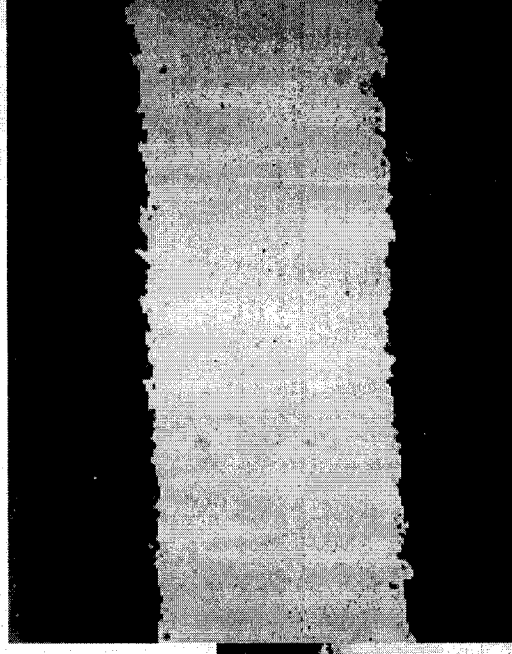
# NIAL CONVERSION



2 hours



4 hours



10 hours

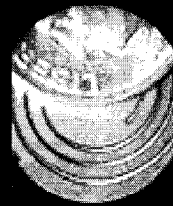


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# RESULTS

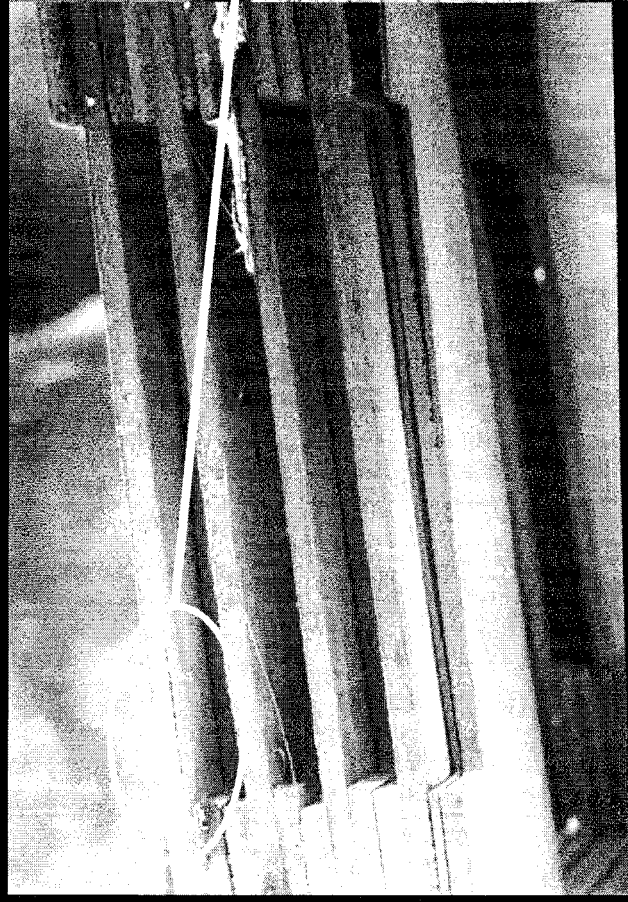


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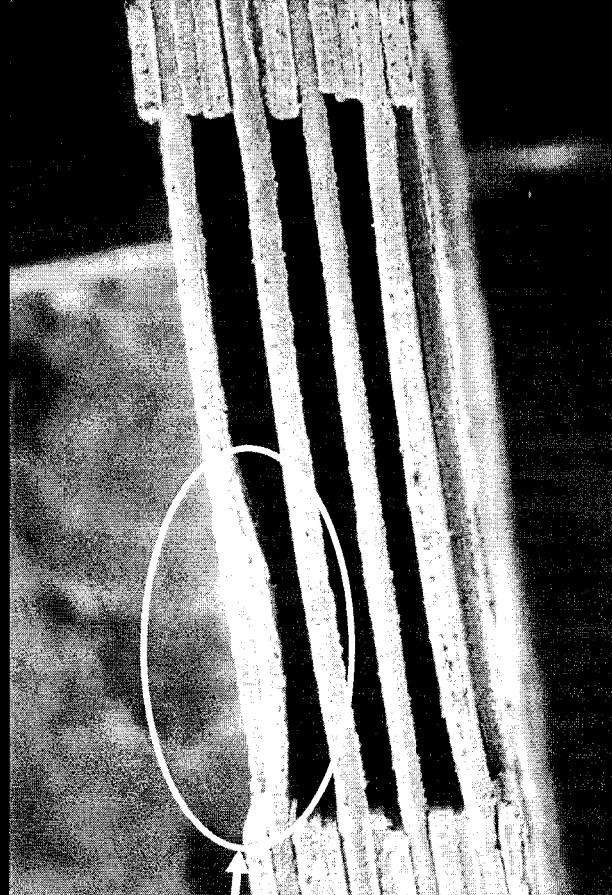


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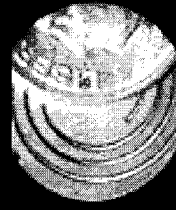
# DELAMINATION



Before Bonding

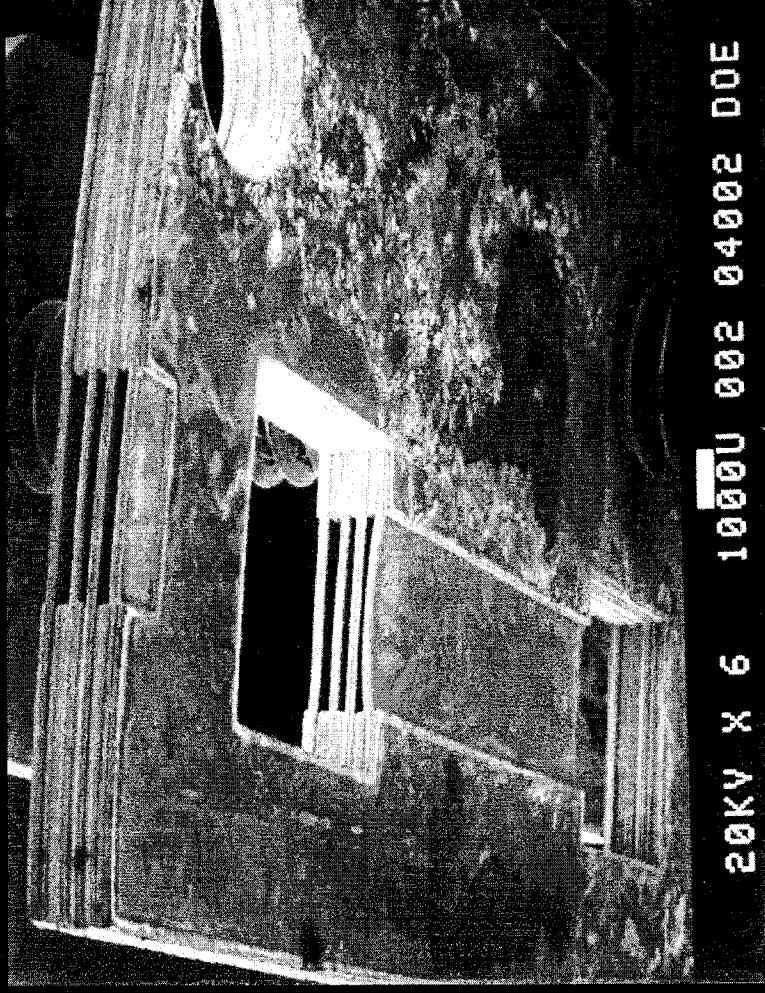


After Bonding

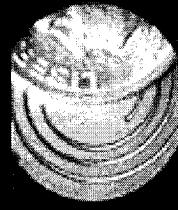


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# FIN DEFLECTION



Caused by triaxial stress from CTE mismatch between jig and device



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# SUMMARY

- Intermetallic microreactor is feasible
- Dimensional control in intermetallic microchannels was demonstrated
- Delamination a source of warpage
  - Other methods of tacking should be investigated such as roll bonding
- Other aluminides to be studied

